



# Characterization of U.S. Army Corps of Engineers Reservoirs: Design and Operational Considerations

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**PURPOSE:** This technical note describes design and operational characteristics of U. S. Army Corps of Engineers (CE) reservoirs as they relate to potential management opportunities through operational change. The reported data serve to identify groups of reservoirs based on their physical and operational characteristics. Subsequent efforts will employ the water quality model CEQUAL-W2 to assess potential benefits due to operational changes.

**BACKGROUND:** Reservoirs are engineered features of the landscape with well-defined structural and operational characteristics (Kennedy 1999). Several important physical attributes, including mean depth, surface area, and flushing rate, are dictated by reservoir location, topography, and hydrology. These attributes are further defined by structural (e.g., dam height, outlet depth, etc.) and operational (e.g., changes in pool elevation, release rates, etc.) characteristics, which, in turn, may influence the water quality of the impounded reservoir.

Since physical differences between reservoirs and small natural lakes preclude the use or reduce the efficacy of many traditional in-lake management strategies (circulation, nutrient inactivation, sediment removal, etc.), management interventions afforded by operational flexibility offer potentially useful alternatives for reservoirs if linkages exist between reservoir attributes, operation and water quality. However, such linkages must be identified and/or better understood if effective operational strategies for water quality management are to be developed and implemented.

Hydrodynamic and water quality models, such as CEQUAL-W2 (Cole and Buchak 1995), offer an opportunity to conduct 'experiments' to assess water quality responses to modifications in operational characteristics. Candidate modifications include changes in the timing, quantity, and depth of water withdrawals, pool volume, and degree or timing of fluctuations in pool elevation (Kennedy 1999). Potential influences of such modifications on water quality include the storage and distribution of heat and materials (Wright 1967), changes in mixing and light regimes (Stráskraba, Tundisi, and Duncan 1993), loss of materials due to flushing, and complex responses by biological communities (e.g., changes in phytoplankton population density or species composition (Reynolds 1997)).

Since operational water quality management strategies are bounded by (1) current project authorizations, (2) water control objectives, and (3) reservoir attributes, experimental manipulations employing hydrodynamic and water quality models should be conducted within groups of reservoirs having similar operational expectations. The results of attempts to identify and describe groups of CE reservoirs with similar attributes and operational objectives are reported here. Identified groups form the basis for the design of subsequent model applications using CEQUAL-W2.

**ANALYTICAL APPROACH:** Descriptive data for 472 CE dams and their associated reservoirs or pools were obtained from the National Inventory of Dams (NID) database (U.S. Army Corps of

Engineers 1999). The NID includes pertinent data (primarily structural and demographic features related to dam safety) for approximately 76,000 dams with structural heights equal to or greater than 7.6 m. Additional data were solicited from District water quality personnel. Two types of variables were included in the resulting consolidated database; those relating to reservoir morphometry and hydrology, and those descriptive of reservoir operations. These data formed the basis upon which cross-sectional analyses were performed.

A concise suite of variables was selected to describe important morphometric and hydrologic characteristics of each of the reservoirs included in the survey database. These included theoretical hydraulic residence time, reservoir mean depth and surface area, and annual fluctuation in pool elevation. Selection was based on relevance to factors demonstrated to influence water quality and reflected efforts to minimize redundancy. These variables and a brief rationale for their inclusion are presented below.

**Theoretical hydraulic residence time ( $R_T$ ; days).** Hydraulic residence time, computed as average reservoir volume divided by annual flow and expressed in days, is a measure of the average length of time water remains in a reservoir (assuming complete and instantaneous mixing). As such,  $R_T$  incorporates information about reservoir hydrology, morphometry, and operation. Residence time and its reciprocal, flushing rate, provide valuable information about hydrologic influences on water quality.

**Mean Depth ( $Z_{\text{mean}}$ ; meters).** Mean depth is computed as average annual pool volume divided by average annual pool surface area, and provides a useful indication of reservoir depth relationships. Mean depth has implications for the mixing of surface water, thermocline formation, and water withdrawal characteristics.

**Average Pool Surface Area (SA; square kilometers).** Surface area summarizes the longitudinal and lateral extent of the reservoir and is an important supplemental water quality index since many external influences on reservoirs occur at the surface (e.g., wind stress, solar input, etc.) or are often assessed on a unit surface area basis (material loading, algal productivity, etc.). For the present purpose, SA has been defined as the average annual surface area.

**Change in Pool Elevation ( $D_{\text{elev}}$ ; meters).** Pools often fluctuate in elevation over daily, monthly, or seasonal timeframes. Unlike average pool elevation, which provides a general indication of pool characteristics,  $D_{\text{elev}}$  addresses the extremes of operation and can provide valuable clues to influences on water quality characteristics.  $D_{\text{elev}}$  was computed as the average difference between minimum and maximum pool elevation throughout an average year.

Rule or guide curves provide valuable information about the manner in which a reservoir project is operated (or intended to be operated) throughout the year. Since it is difficult to express complex, temporal changes in pool volume and elevation as a single numeric value, a categorical evaluation was requested during the survey. The categories were based on the idealized rule curves exhibited in Figure 1. While it is acknowledged that these categories may not have been sufficiently descriptive of actual rule curves for active projects, survey respondents were asked to make every effort to generalize operational scenarios understanding that the survey sought to identify commonalities rather than differences. These rule curve categories are described below:

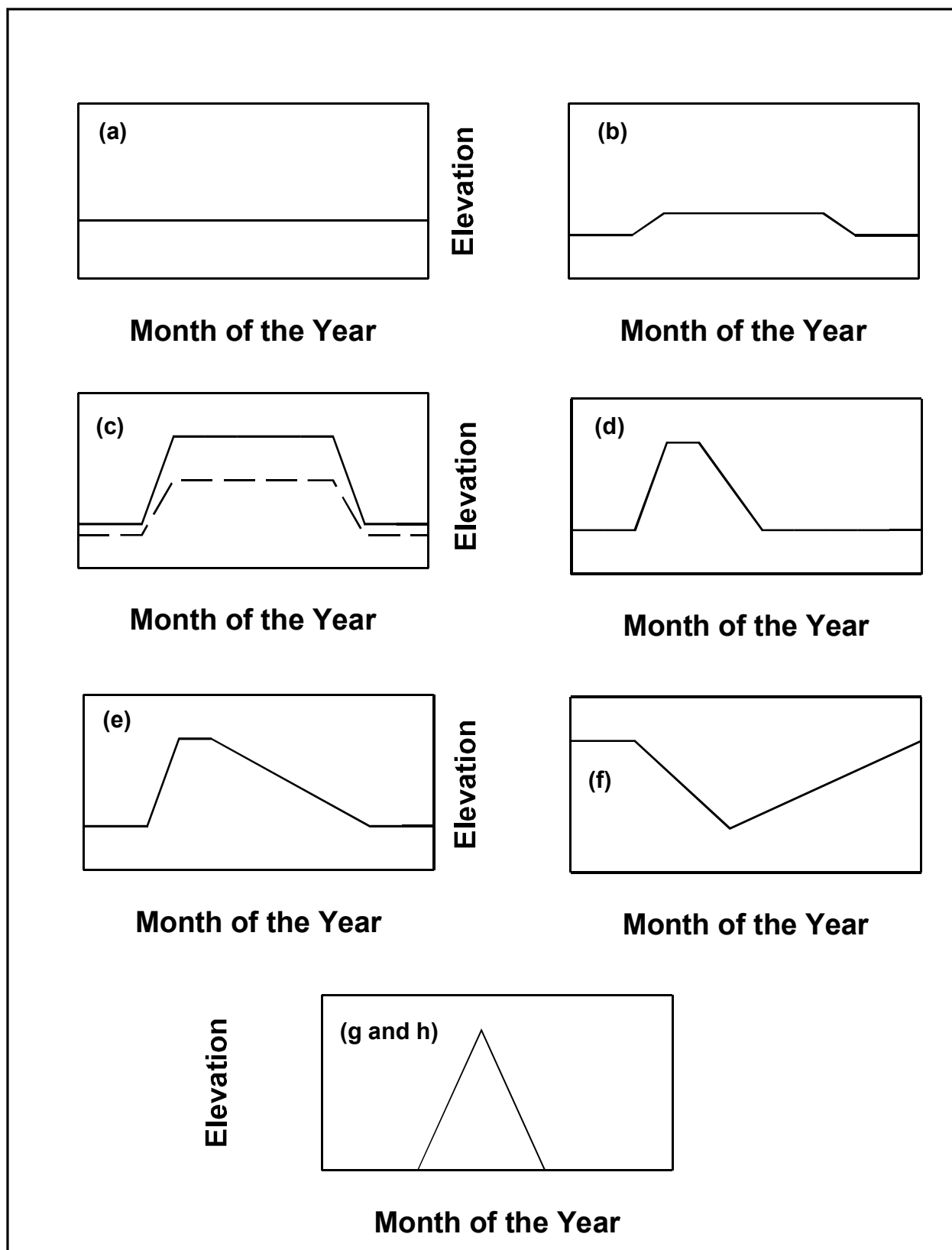


Figure 1. Idealized rule or guide curves for Corps water resource development projects

- **Curve type a.** Pool is maintained at or near a constant elevation.
- **Curve type b.** Similar to Curve a above, except that small increases in elevation are planned from spring through fall.
- **Curve type c.** Significant increases in elevation occur from spring through fall with a relatively stable pool during the summer. Such rule curves are often employed for projects that require an elevated summer conservation or hydropower pool. Such projects are often operated between an upper (solid line in Figure 1) and lower (dashed line in Figure 1) limit.
- **Curve type d.** This rule curve allows floodwater to be stored for relatively short periods of time after which pool elevation is decreased to pre-flood levels.
- **Curve type e.** Similar to Curve d above, except that releases of water stored during the spring high flow period occur over a relatively long period of time (often not returning to low levels until late in the year).
- **Curve type f.** Pool elevation declines during a portion of the year as storage is depleted to meet release objectives (e.g., summer low flow) or consumptive uses (e.g., irrigation). Pool elevation increases after release needs are met (and sufficient inflow volume is available). In some cases, increases in pool volume require relatively long periods of time.
- **Curve type g.** Rule curve associated with the operation of 'dry dams.' A small minimum pool is maintained through much of the year (often as a means to provide recreation or fish and wildlife benefits). The curve allows significant, short-term increases in pool elevation for flood storage.
- **Curve type h.** A curve type similar to Curve g described above for 'dry dams,' except that the permanent pool is lacking or extremely limited in size. (This curve type was added based on survey results.)
- **Curve type o.** A category for those projects that do not fit any of the curve types described above.

Based on survey responses, a total of 229 Corps water resource projects were included in the assessment database. The geographic distribution of these projects relative to Corps Division boundaries is presented in Figure 2 and the number of projects identified for each rule curve type are listed by Corps Division in Table 1.

**ASSESSMENT RESULTS:** Morphometric and hydrologic characteristics varied widely among Corps projects included in the final assessment database (Figure 3). Median  $Z_{\text{mean}}$  and  $R_T$  (4.54 m and 22.4 days, respectively) were similar to those determined for all Corps projects contained in the NID database (median  $Z_{\text{mean}}$  and  $R_T$  were 4.55 m and 29.9 days, respectively), indicating little bias associated with survey responses. However, the median value of SA for NID projects was markedly higher than that for surveyed projects (14.79 versus 7.04 km<sup>2</sup>, respectively). The distribution in SA for surveyed projects displayed strong negative skew due to the inclusion of several 'dry dams' with extremely small values for SA. Their inclusion also resulted in negative skew in the distribution of  $Z_{\text{mean}}$  values. Similarly skewed distributions were observed for NID projects.  $D_{\text{elev}}$ , available only for surveyed projects, had a median value of 2.67 m.



Figure 2. Map indicating the locations of Corps water resource development projects included in this assessment

**Table 1**  
**Distribution of Rule Curve Types Across Corps Divisions (Based on Survey Responses)**

Curve Type	Corps Division						
	NAD	SAD	LRD	MVD	SWD	NWD	SPD
A	11	4	26	6	14	15	0
B	1	0	5	0	6	0	0
C	3	2	16	0	0	0	0
D	20	3	0	7	3	0	0
E	0	0	8	4	1	0	0
F	1	0	0	0	0	2	1
G	1	0	3	2	0	0	4
H	13	0	1	1	4	0	10
O	0	0	0	1	26	0	0

Operational strategies associated with each surveyed project, as defined by rule curve type, were assigned based on survey responses. The distribution of projects across rule curve types is presented in Table 1 and Figure 4. While not available for all surveyed projects, observed operational data (pool elevation, inflow, and outflow) for selected projects were compared to rule curves as a means to confirm survey responses and to assess variability. Data for J. Percy Priest Reservoir (rule curve type *c*), Barkley Reservoir (rule curve type *d*), and Old Hickory Reservoir (rule curve type *a*) are typical examples of operational performance (Figure 5).

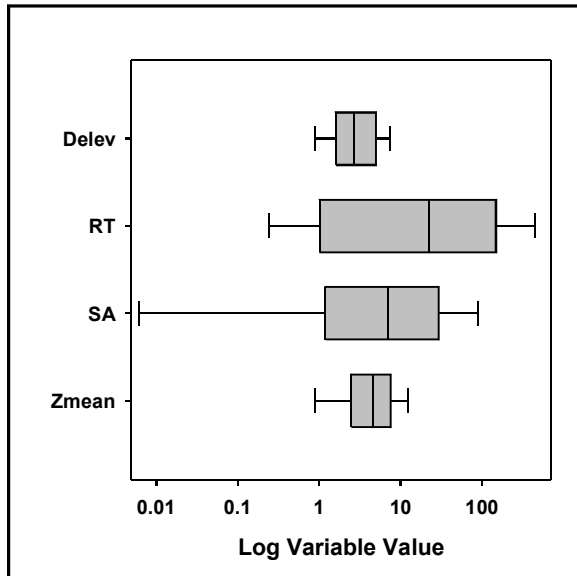


Figure 3. Frequency distribution of reservoir attribute values for 229 Corps water resource development projects.  $Delev$  = average annual fluctuation in pool elevation (meters);  $RT$  = theoretical hydraulic retention time (days);  $SA$  = average pool surface area; and  $Z_{mean}$  = average pool mean depth

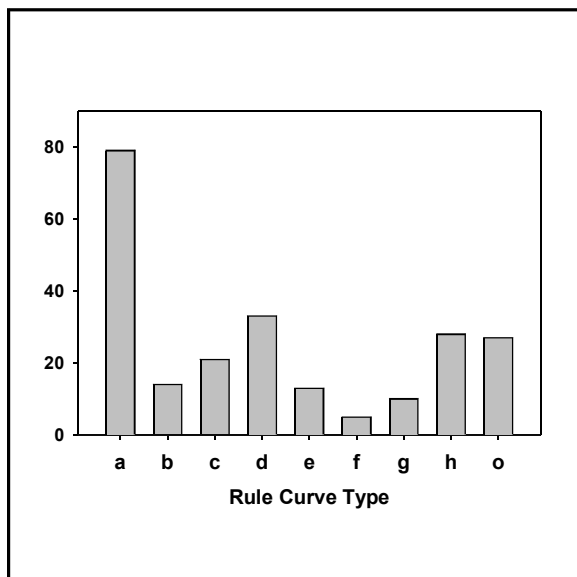


Figure 4. Distribution of projects by rule curve type (based on survey responses)

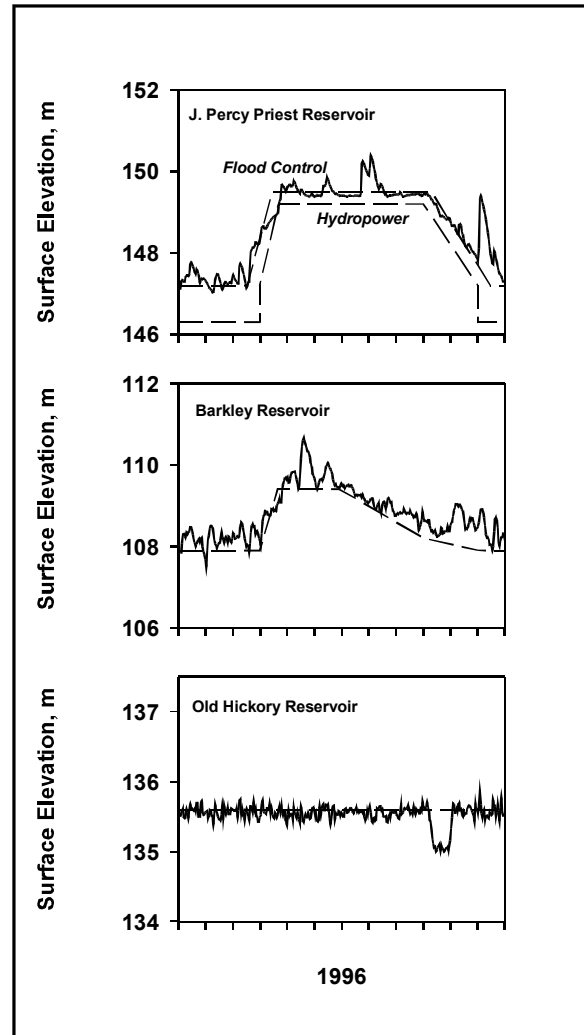


Figure 5. Rule curves (dashed line) and observed daily changes in reservoir elevation (solid line) for selected Corps reservoirs. Rule curves correspond to curve type *c* (J. Percy Priest Reservoir), curve type *d* (Barkley Reservoir), and curve type *a* (Old Hickory Reservoir)

Morphometric and hydrologic characteristics exhibited marked variability among and between rule curve types (Figures 6a and 6b). SA values ranged over five orders of magnitude with projects of extremely limited area associated with rule curve types *a*, *d*, and *h*. These rule curve types, as well as rule curve type *g*, also included projects with the shallowest mean depths (< 2 m). Distributions in values of  $R_T$ , while highly variable (e.g., those for rule curve type *a* ranged from <1 day to 1,000 days) displayed patterns relative to rule curve type. In general, projects associated with rule curve types *c*, *e*, *f*, and *o* had longer water residence times while those associated with rule curve types *h* and *g* had relatively short times. Changes in pool elevation ( $D_{elev}$ ) varied widely (0.1 to 52 m), with greatest values being associated with rule curve types *a*, *c*, *e*, and *f*. Projects with limited fluctuations in pool elevations were operated according to rule curve types *a*, *d*, and *h*.

Based on comparisons across rule curve types, those groups exhibiting broad ranges in characteristics were further assessed using cluster analysis. Included in the analyses were rule curve types *a*, *c*, *d*, and *h*. Analyses were based on the above four project attributes (SA,  $Z_{mean}$ ,  $R_T$ , and  $D_{elev}$ ). For each project, character values were converted to numeric values corresponding to quartile number (i.e., 1-4) based on the distributions of values for all projects in the assessment database. The result was the identification of 13 distinct rule curve groups (Table 2). These groups were assigned categorical descriptions as a means to generalize about the characteristics of each group (Table 2).

Rule curve groups identified here represent reasonably homogeneous associations of Corps reservoirs and will form the basis for subsequent assessments of potential water quality influences of operational strategies employing CEQUAL-W2. Model assessments of representative reservoirs for each rule curve group address the importance of differences in physical, hydrologic, and operational characteristics.

**SUMMARY:** Linkages among project purpose, design, and operation have potentially important influences on water quality. Understanding these interactions provides an information base upon which to evaluate the water quality benefits associated with operational management alternatives. Since operational ‘experiments’ involving changes to project operation, and the associated monitoring of water quality responses, are expensive and difficult to implement, water quality models offer a reasonable assessment alternative. Selected physical, hydrologic and operational characteristics of Corps reservoirs are compared here. These comparisons identify groups of reservoirs with similar characteristics and operational strategies. These groups will form the basis for applications of CEQUAL-W2, thus ensuring a robust assessment of the potential water quality benefits of operational changes.

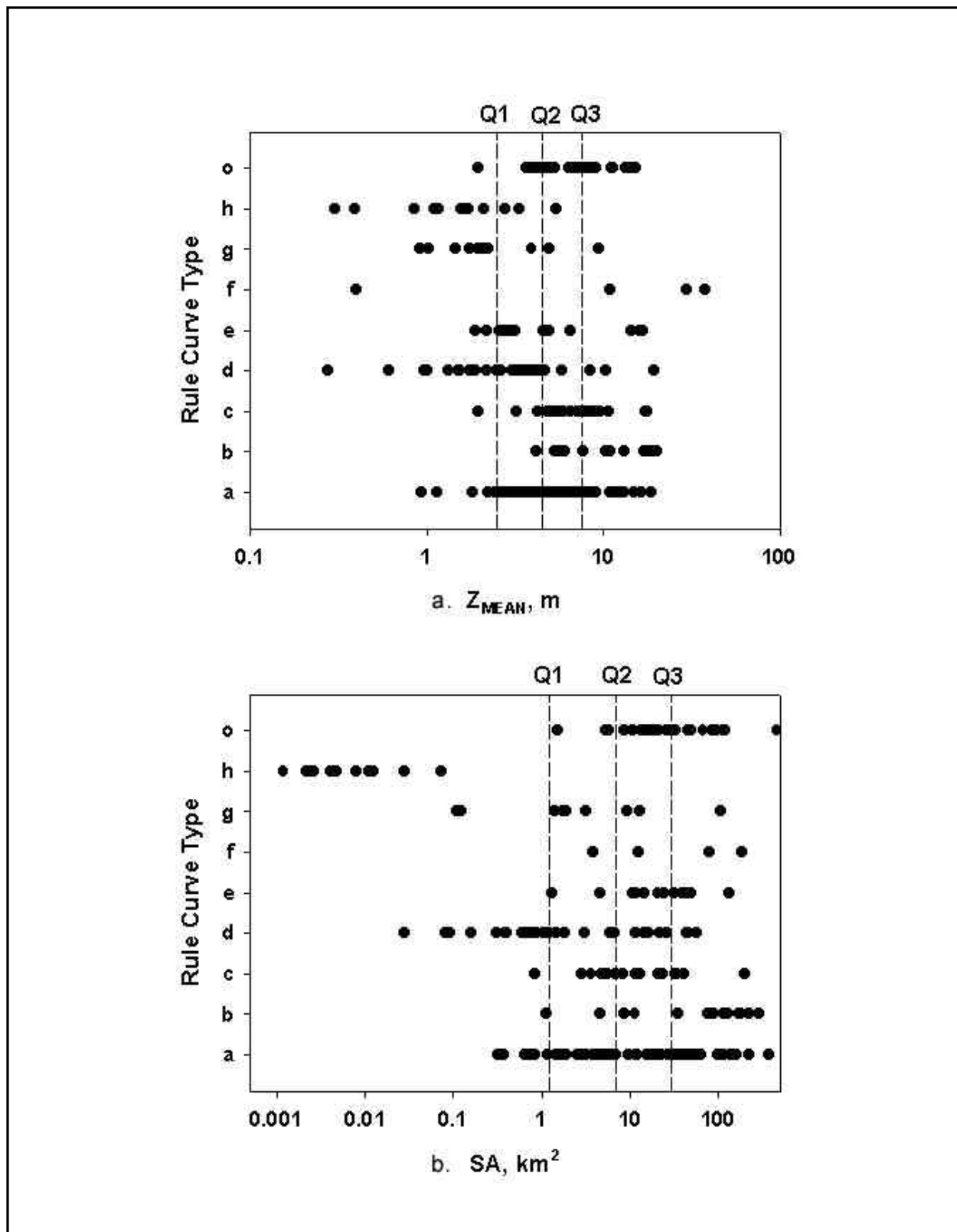


Figure 6. Curve-specific distributions of Corps reservoir projects (symbols). Vertical dashed lines indicate the upper boundaries of the first (Q1), second (Q2; median), and third (Q3) quartiles of the distribution for all surveyed projects (see Figure 3) (Continued)



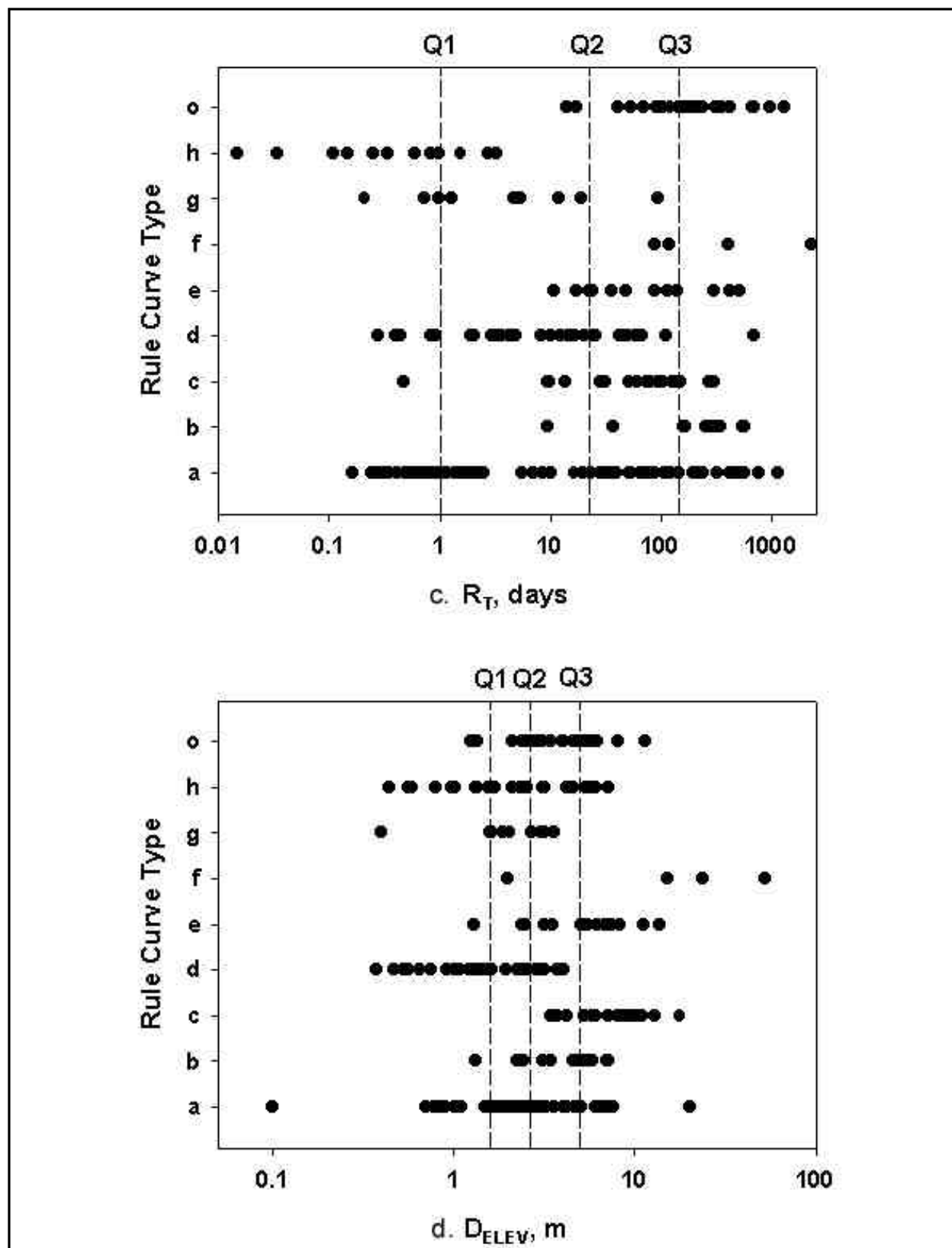


Figure 6. (Concluded)

**Table 2**  
**Median Values and Interquartile Ranges (parentheses) for Selected Reservoir Characteristics Grouped by Rule Curve Type. Categorical Descriptors for Each Rule Curve Type were Based on Evaluation of Relative Distributions of Reservoir Characteristics**

Rule Curve Group	n	SA, km <sup>2</sup>	Z <sub>mean</sub> , m	R <sub>T</sub> , days	D <sub>elev</sub> , m
A1	55	4.6 (12.9) Small	4.3 (2.3) Shallow	1 (9) Very Short	2.3 (1.5) Small
A2	24	40.0 (377.2) Large	7.1 (5.8) Moderate	283 (444) Long	2.2 (4.2) Small
B	14	82.4 (286.6) Large	10.9 (11.8) Moderate	271 (552) Long	4.8 (2.4) Moderate
C1	17	12.3 (16.4) Moderate	8.2 (2.8) Moderate	79 (75) Moderate	8.8 (4.3) Large
C2	4	4.3 (2.80) Small	3.7 (2.0) Shallow	10 (7) Short	7.6 (4.0) Large
D1	27	0.8 (1.5) Small	2.5 (2.1) Shallow	5 (15) Short	1.1 (1.0) Small
D2	6	35.1 (23.8) Moderate	3.1 (2.4) Shallow	54 (18) Moderate	2.4 (1.2) Small
E	13	20.6 (28.2) Moderate	3.2 (3.9) Shallow	48 (116) Moderate	5.4 (4.3) Moderate
F	4	46.8 (126.3) Large	20.4 (28.3) Deep	262 (1,251) Long	19.2 (29.5) Very Large
G	10	1.9 (7.9) Small	2.0 (2.5) Shallow	5 (11) Short	1.9 (1.4) Small
H1	10	<0.1 (<0.1) Small	0.3 (0) Very Shallow	<1 (<1) Very Short	5.4 (1.9) Moderate
H2	18	<0.1 (<0.1) Small	1.0 (1.4) Shallow	<1 (1) Very Short	1.4 (1.0) Small
O	27	28.8 (35.3) Moderate	7.0 (3.9) Moderate	206 (321) Long	3.9 (2.6) Moderate

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